ARMY RESEARCH LABORATORY

Status Report on SPS TiB_2/TiB/Ti Functionally Graded Materials (FGMs) for Armor

by James W. McCauley, G. D'Andrea, Kyu Cho, Matthew S. Burkins, Robert J. Dowding, and William A. Gooch, Jr.

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14. ABSTRACT The pioneering research by Wilkins and colleagues in the 1960s led many investigators to conclude that ceramic armor performance could be significantly enhanced with materials macrostructurally designed to grade from a pure ceramic to a stiff, more ductile material at the back surface. Several configurations of TiB_2/TiB/Ti functionally graded materials were fabricated using a spark plasma sintering process. Detailed microstructural characterization of the as-processed material is presented as well as x-ray flash radiographs of penetrating projectiles in a reverse ballistic configuration using a 1-MeV x-ray system in a 100-mm gas gun apparatus. This report is a collection of the charts used for an oral presentation at the 28th International Cocoa Beach Conference and Exposition on Advanced Ceramics and Composites.					
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1. Introduction

Ceramics were first used extensively in body armor and helicopter seats during the Vietnam era, when work on armor ceramics reached its first peak on both opaque and transparent glass and ceramic materials. Much of the early work starting in the mid 1960s was guided by the pioneering modeling research of Mark Wilkins and colleagues from the Lawrence Radiation Laboratory, mostly focusing on thin ceramic armor plates. This pioneering research led many investigators to conclude that ceramic armor performance could be significantly enhanced with materials macrostructurally designed to grade from a pure ceramic to a stiff, more ductile material at the back surface. In recent years, these types of materials have been referred to as functionally graded materials (FGMs).

Seven samples of TiB_2/TiB/Ti FGMs were fabricated by Masao Tokita and Masakazu Kawahara, Sumitomo Coal Mining Co. Ltd., Tokyo, Japan, using a spark plasma sintering (SPS) process. Materials with four, five, and six layers with varying grading schemes of Ti, TiB, and TiB_2 were produced. Characterization of the material was carried out, including x-ray radiographic CT scans by Mr. William Green and detailed x-ray diffraction and field emission scanning electron microscopic microstructural analysis by Mr. Kyu Cho, both of the U.S. Army Research Laboratory (ARL), Aberdeen Proving Ground, MD.

A series of the samples were then tested in low and high velocity impact tests. Professor Kasano of the Takushoku University, Tokyo, Japan, carried out low-velocity impact tests and high-speed photography on one FGM sample (FGM 1–4). Matthew Burkins and William Gooch then used the ARL 100-mm reverse ballistics gas gun facility with a 1-MeV x-ray system to get real time radiographs of the FGM material with comparison to monolithic TiB_2 material. No dramatic improvements over the monolithic material were observed in these tests.

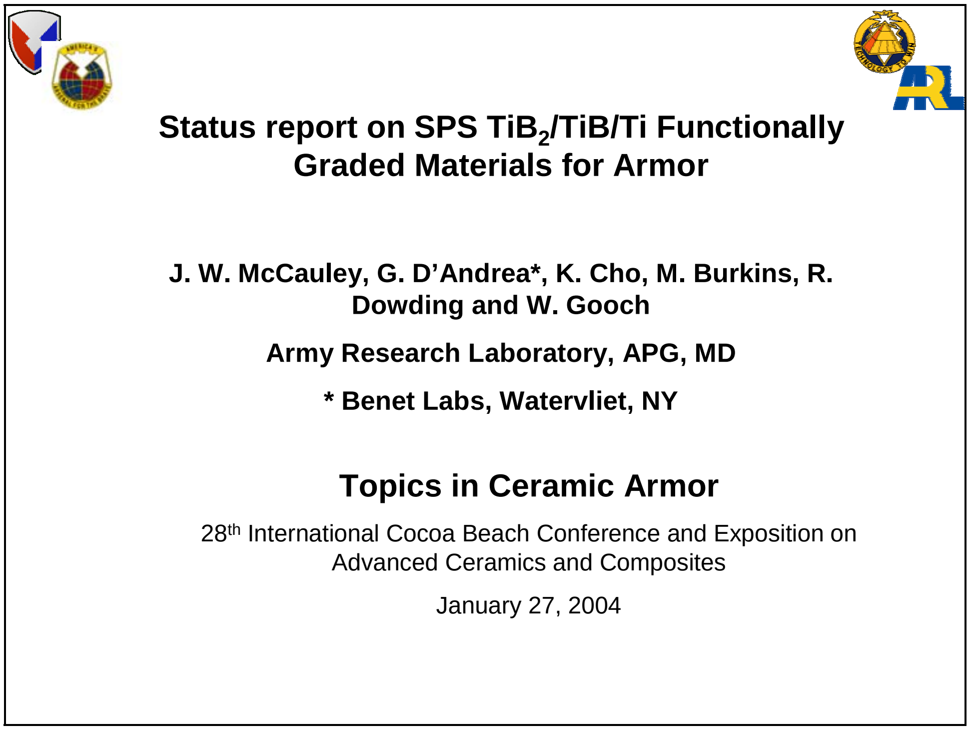


Figure 1. Status report on spark plasma sintering (SPS) TiB_2/TiB/Ti functionally graded materials (FGMs) for armor.

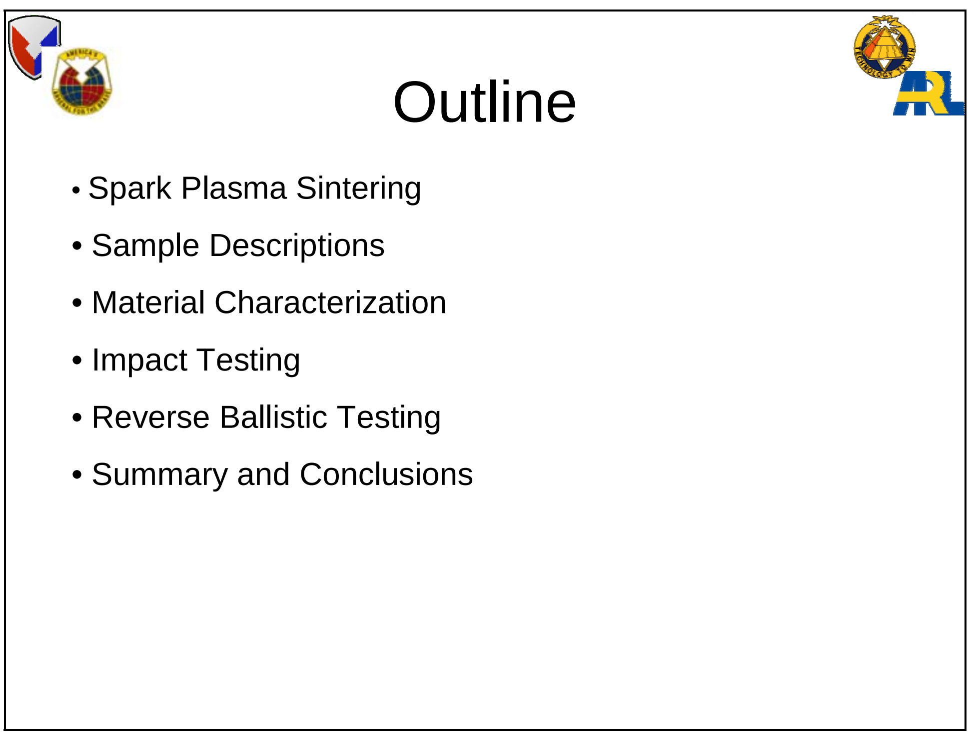


Figure 2. Outline.

Spark Plasma Sintering

Spark Plasma Sintering at Sumitomo Coal Mining Company, Ltd., Tokyo, Japan:

Masao Tokita and Masakazu Kawahara

Figure 3. SPS.

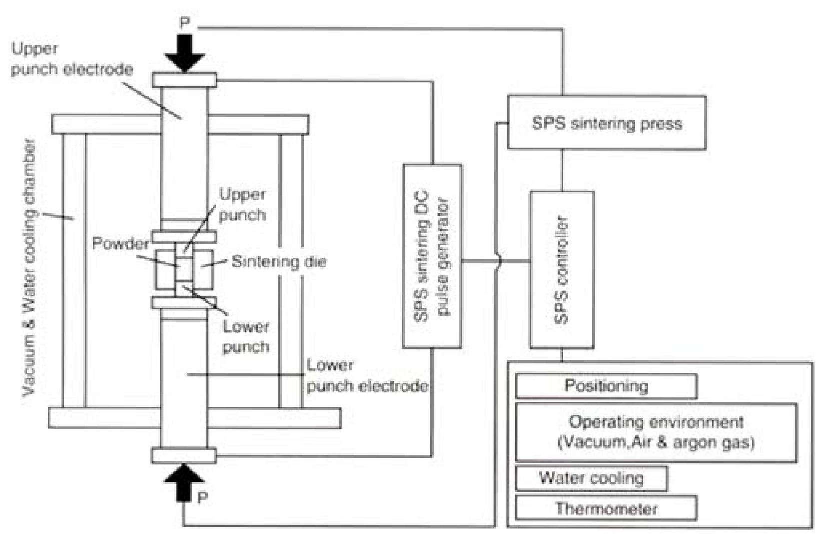


Figure 3: SPS system configuration

Figure 4. SPS system configuration.

Spark Plasma Sintering at Sumitomo Coal Mining Company, Ltd., Tokyo, Japan: Masao Tokita and Masakazu Kawahara

Figure 5. SPS at Sumitomo Coal Mining Company, Ltd., Tokyo, Japan: Masao Tokita and Masakazu Kawahara.

TiB_2/Ti FGMs by SPS: Sumitomo Coal Mining Company

All FGM Materials = 10-mm thick except FGM 1-1 (9 mm)

Sample No.	Layer No.	Composition(wt%) TiB2	TiB	Ti	Thickness (mm)	Theoretical density	Actual density
1- 1	1	-	80	20	3		
	2	-	50	50	1		
	3	-	30	70	1	4.77	4.55
	4	-	10	90	2		(95.4%)
	5	-	0	100	2		
1- 2	1	85	15	-	3		
	2	-	30	70	2	4.55	4.44
	3	-	10	90	2		(97.6%)
	4	-	0	100	3		
1- 3	1	85	15	-	3		
	2	-	30	70	2		
	3	-	20	80	1	4.53	4.46
	4	-	10	90	1		(98.5%)
	5	-	0	100	3		
1- 4	1	85	15	-	3		
	2	-	40	60	1		
	3	-	30	70	1	4.58	4.46
	4	-	20	80	1		(97.4%)
	5	-	10	90	1		
	6	-	0	100	3		
1- 5	1	85	15	-	3		
	2	-	40	60	1		
	3	-	30	70	1	4.58	4.47
	4	-	20	80	1		(97.6%)
	5	-	10	90	1		
	6	-	0	100	3		
1- 6	1	85	15	-	3		
	2	-	40	60	1		
	3	-	30	70	1	4.58	4.47
	4	-	20	80	1		(97.6%)
	5	-	10	90	1		
	6	-	0	100	3		
1- 7	1	85	15	-	3		
	2	-	40	60	1		
	3	-	30	70	1	4.58	4.47
	4	-	20	80	1		(97.6%)
	5	-	10	90	1		
	6	-	0	100	3		

Ballistic Test

Ballistic Test

Characterization

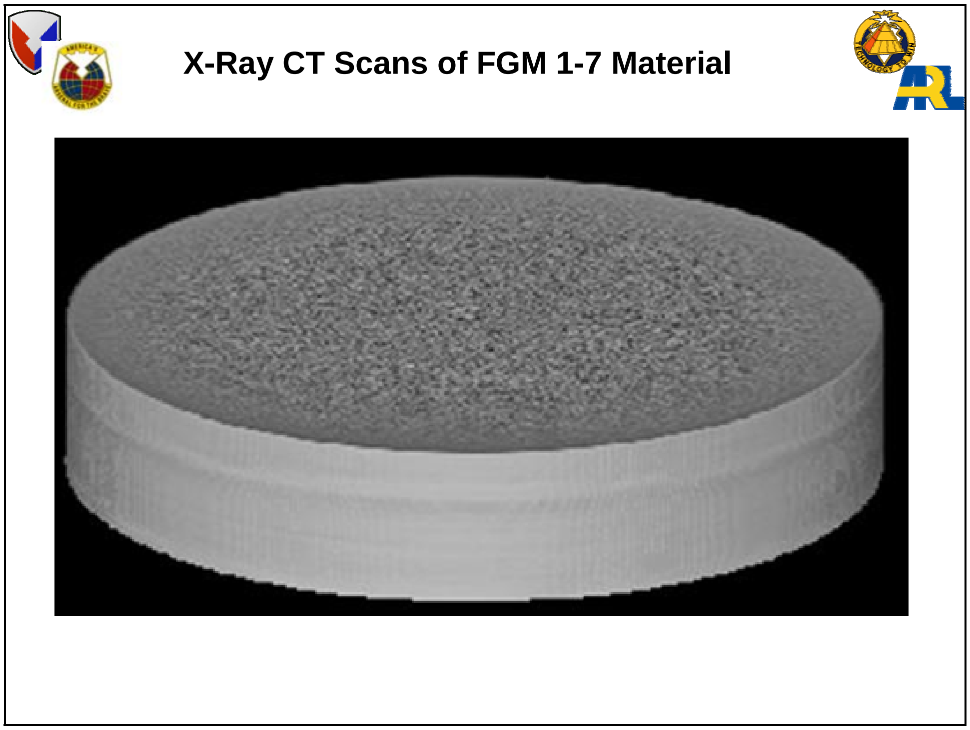
Broke

Impact testing: Takushoku University: Kasano

Characterization

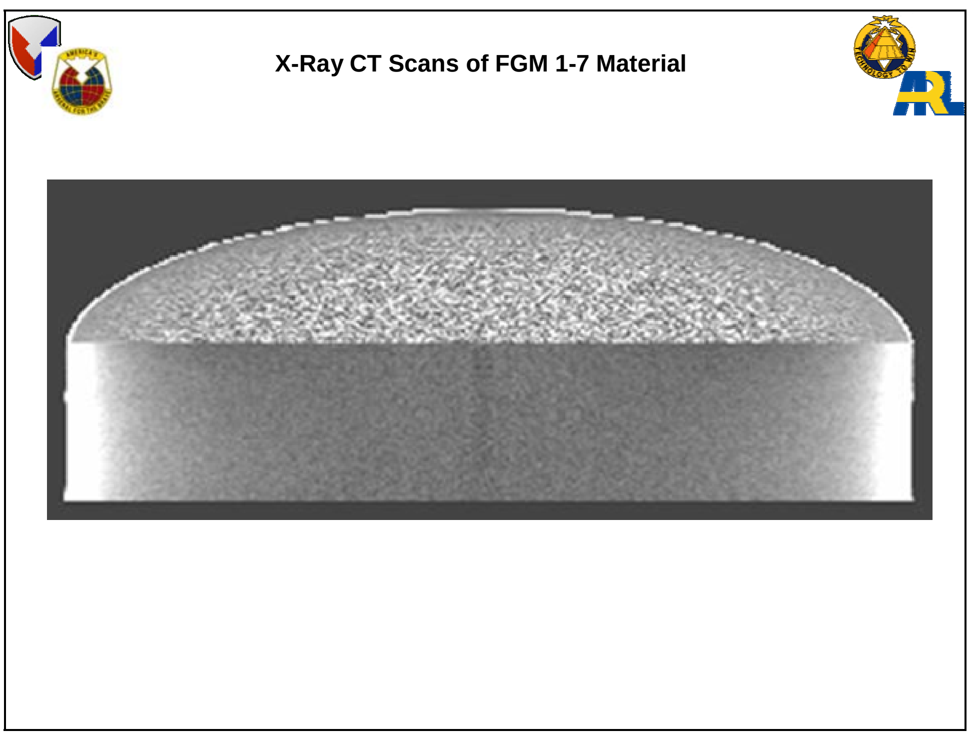
CT Scan and Ballistic Test

Figure 6. TiB_2/Ti FGMs by SPS: Sumitomo Coal Mining Company.



Source: William Green, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD.

Figure 7. X-ray CT scans of FGM 1–7 material.



Source: William Green, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD.

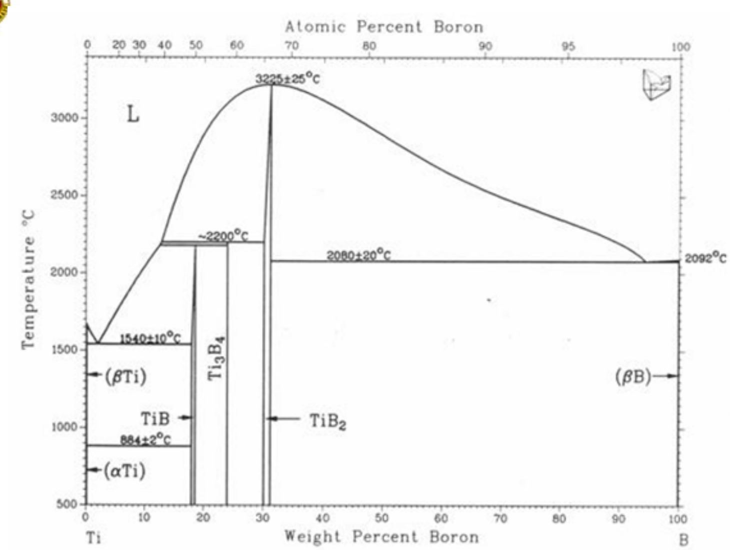
Figure 8. X-ray CT scans of FGM 1–7 material.

Functionally Graded Materials
Spark Plasma Sintering (SPS)
TiB_2/TiB/Ti

5- layer material (FGM 1-3)

Layer	TiB_2 (%)	TiB (%)	Ti (%)	Thick (mm)
1	85	15	—	3
2	—	30	70	2
3	—	20	80	1
4	—	10	90	1
5	—	—	100	3

Figure 9. Functionally graded materials SPS TiB_2/TiB/Ti: five-layer material (FGM 1–3).



Source: J. L. Murray, P. K. Liao, and K. E. Spear, *Bull. Alloy Phase Diagram* **1986**, *7* (6), 550–555 and 587–588.

Figure 10. Ti-B phase diagram.

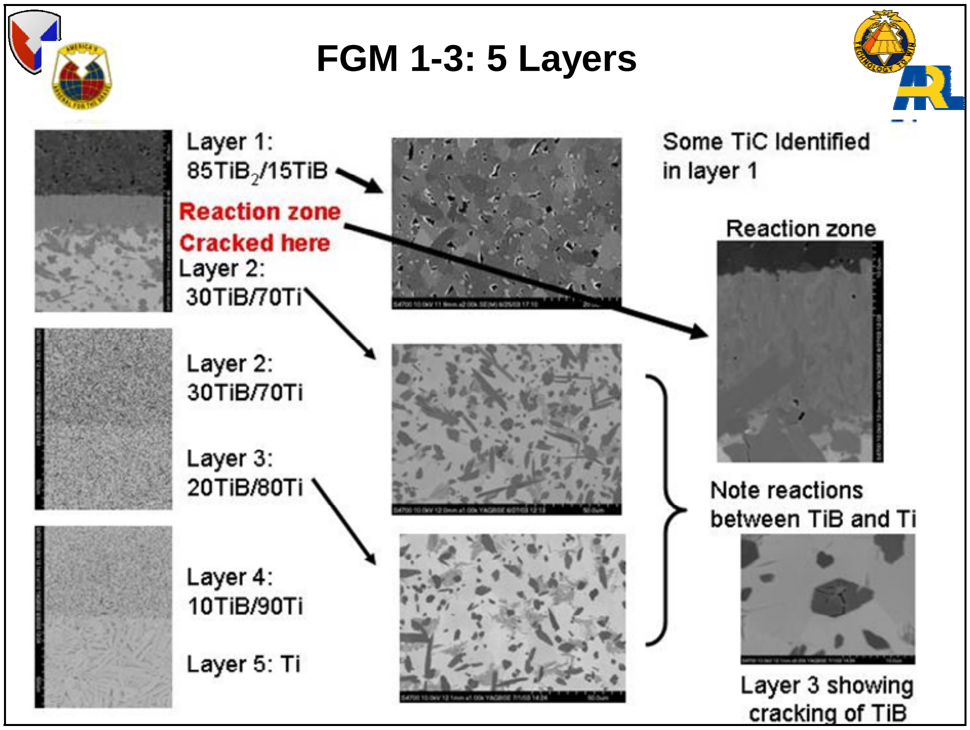


Figure 11. FGM 1–3: five layers.

Functionally Graded Materials

Spark Plasma Sintering (SPS)

TiB_2/TiB/Ti

6-layer material (FGM 1-6)

Layer	TiB_2 (%)	TiB (%)	Ti (%)	Thick (mm)
1	85	15	—	3
2*	—	40	60	1
3	—	30	70	1
4	—	20	80	1
5	—	10	90	1
6	—	0	100	3

*** 5-layer material eliminates layer-2**

Figure 12. Functionally graded materials SPS TiB_2/TiB/Ti: six-layer material (FGM 1–6).

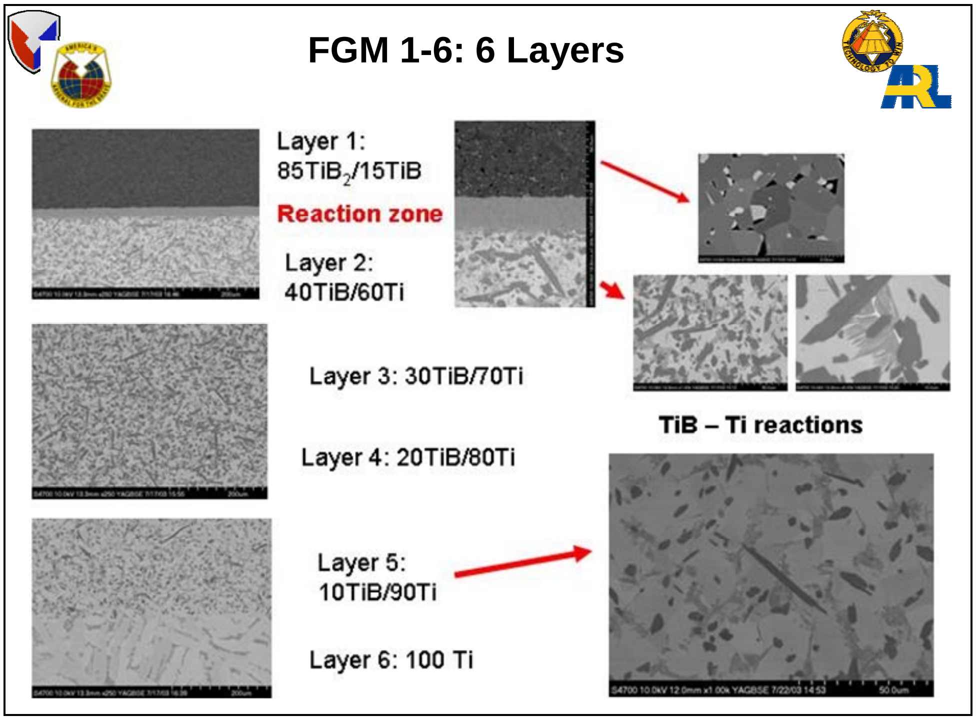


Figure 13. FGM 1–6: six layers.

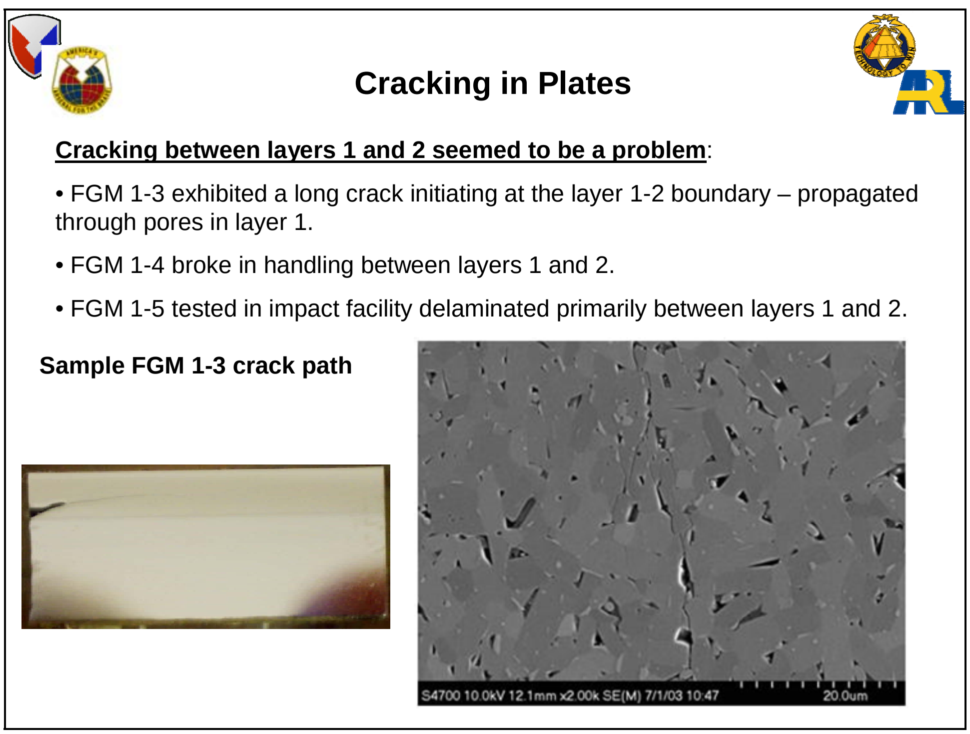


Figure 14. Cracking in plates.

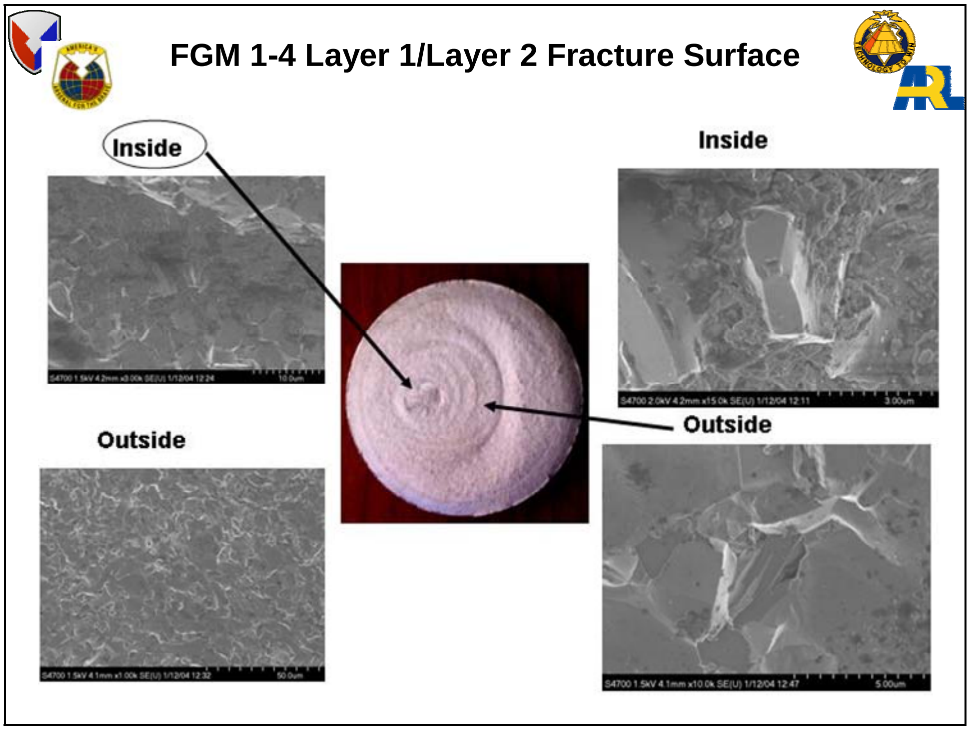
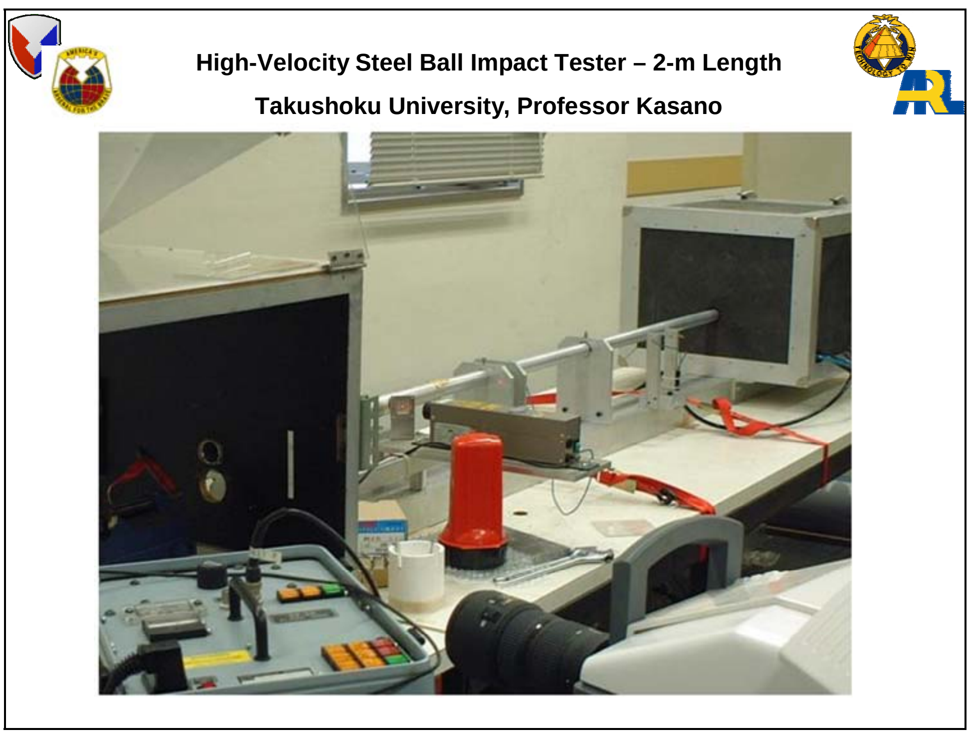
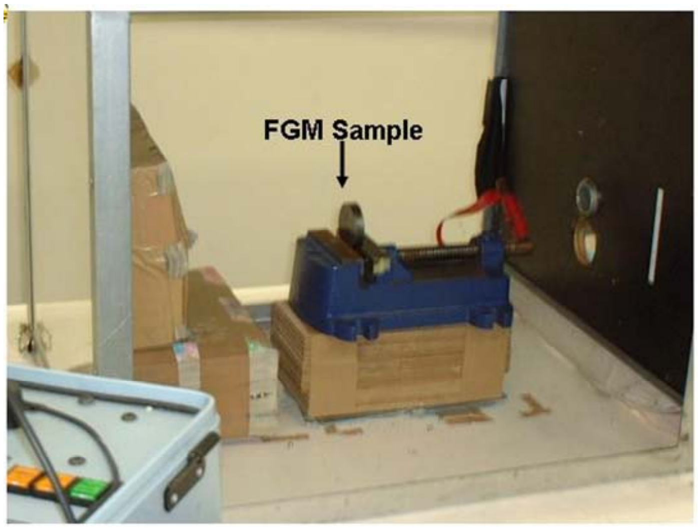


Figure 15. FGM 1–4: layer 1/layer 2 fracture surface.



Source: Takushoku University, Professor Kasano.

Figure 16. High-velocity steel ball impact tester; 2-m length.

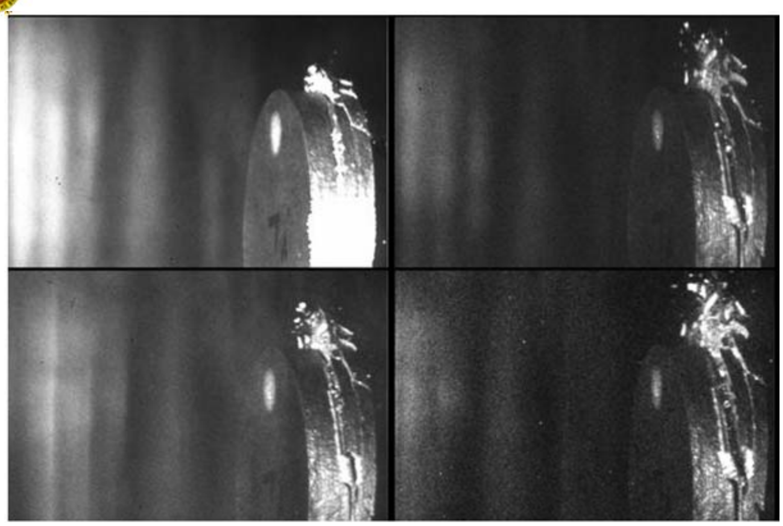


Steel ball = 5 mm diameter; 0.5 g

Velocity = 240 m/s

Figure 17. FGM sample.

High-Speed Photography of Impact on TiB_2 Side



First impact carried out on the Ti side caused a dimple; second impact (same sample) on TiB_2 side caused delaminations and fracturing of layer 1.

Figure 18. High-speed photography of impact on TiB_2 side.

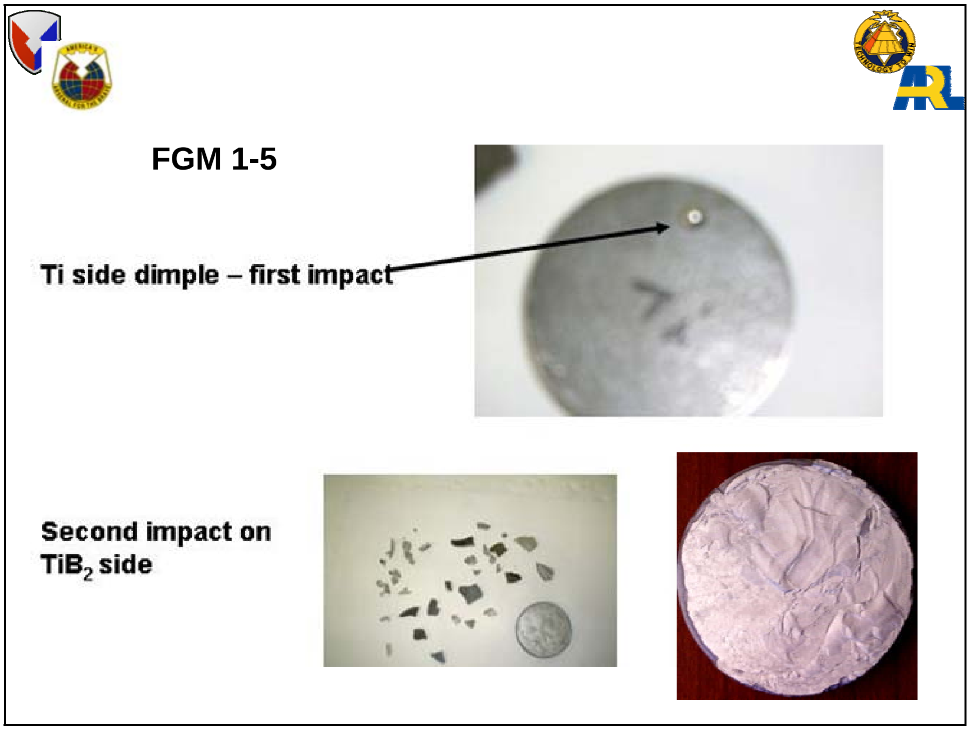


Figure 19. FGM 1–5.

Figure 20. The 100-mm reverse ballistics gas gun facility with 1-MeV x-ray systems.

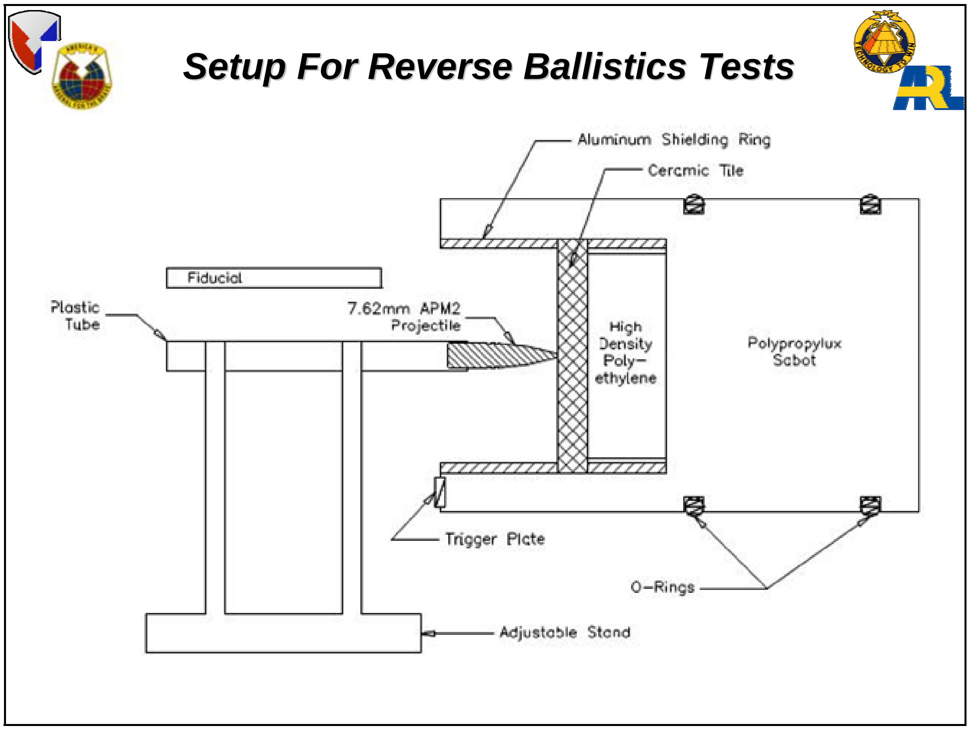


Figure 21. Setup for reverse ballistics tests.

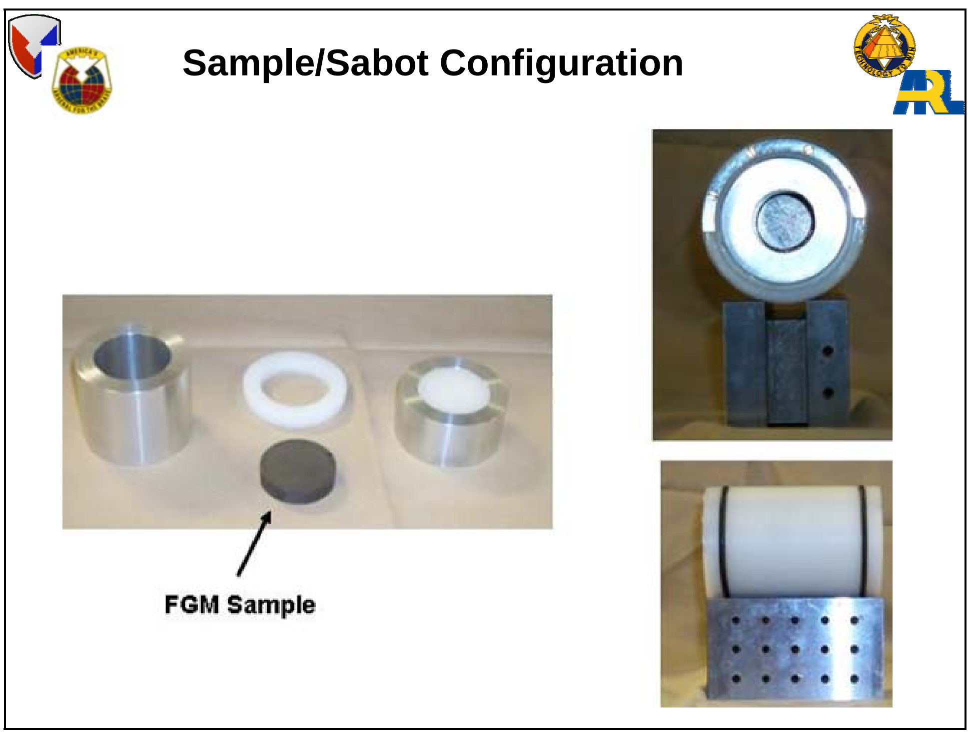


Figure 22. Sample/sabot configuration.

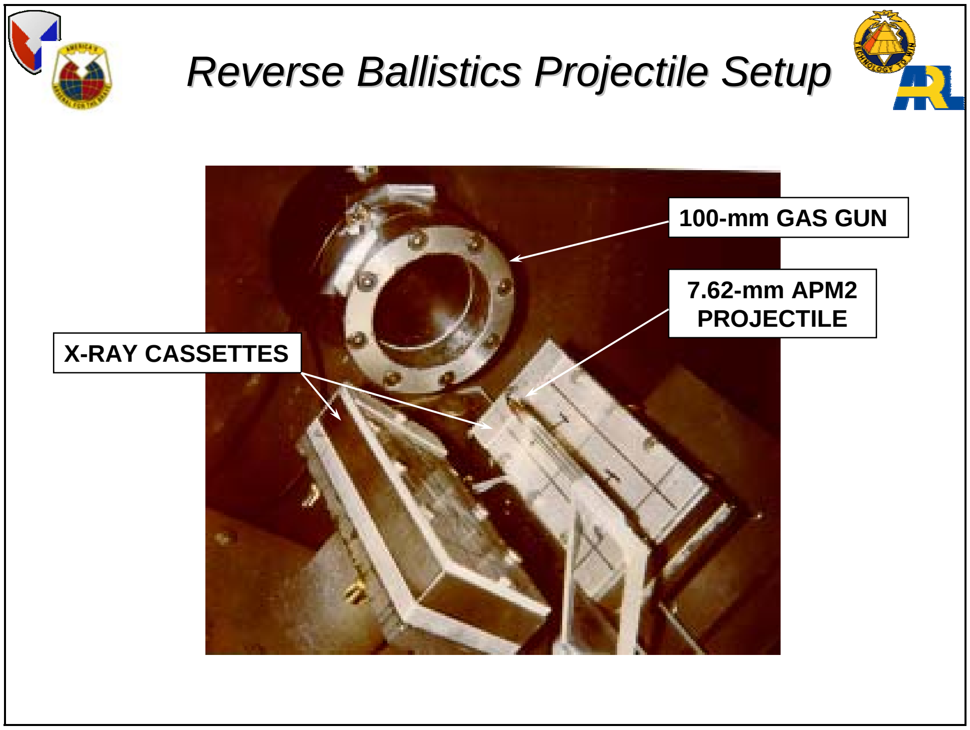


Figure 23. Reverse ballistics projectile setup.

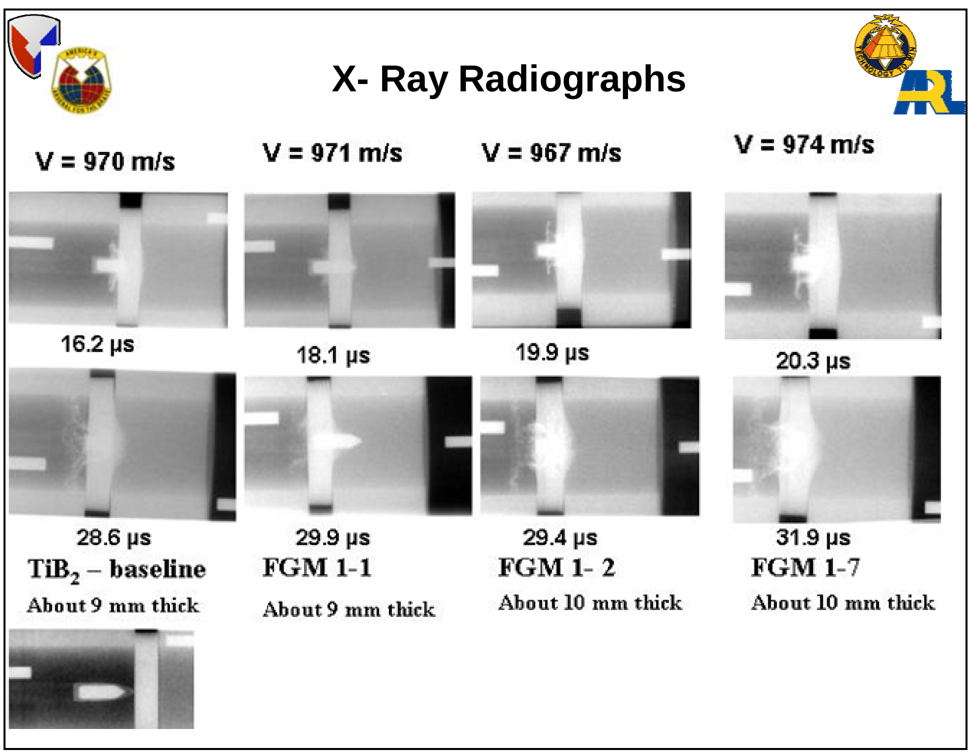


Figure 24. X-ray radiographs.

2. Summary and Conclusions

- SPS has been successfully used to fabricate TiB_2/TiB/Ti FGMs with densities approaching 98% of the calculated theoretical density.
- In the configurations fabricated, issues remain concerning the interface between the top TiB_2/TiB layer and the underlying layers.
- Significant reaction and cracking (delamination) occur at this interface.
- Moderate velocity impact tests also exhibit this delamination.
- Reverse ballistic tests indicate that the four- and six-layer TiB_2 top layer FGM samples exhibited results comparable to the baseline monolithic TiB_2.
- These preliminary results, using SPS to fabricate FGM samples, suggest that much more systematic work is warranted, especially between the top TiB_2 layer and the succeeding layers.
- Future optimization of functionally graded TiB_2/TiB/Ti materials should be supported by systematic modeling of a variety of configurations.

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